

HIGH CURRENT, LOW JITTER, EXPLOSIVE CLOSING SWITCHES*

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Abstract

Isentropic compression experiments (ICE) using a high explosive pulsed power (HEPP) system have been developed to obtain isentropic equation of state data for metals at megabar pressures [1][2]. The HEPP system comprises a magnetic flux compressor, an explosively-driven opening switch and a series of closing switches; fast rising current pulses are produced, with rise times of ~500 ns at current densities exceeding many MA/cm. These currents create continuous magnetic loading of the metals under study. The success of these experiments depends on the precise control of the current profile, and that in turn depends on the precise timing of the closing switches to within 50 ns at currents of the order 10 MA and voltages of ~150 kV. We first used Procyon closing switches [3] but found their timing to be unacceptably imprecise for ICE with a jitter of typically 600 ns. We suspected that the switch timing was sensitive to applied voltage; this was subsequently confirmed by experiment, as we will show. A simple shock model was developed to explain the voltage sensitivity of closure time, dt/dV , and from the model we designed a low jitter switch that uses the shock-induced electrical conduction of polyimide. The predicted dt/dV was exactly equal to the measured value, thus confirming the model. This new switch design proved successful and met the 50 ns criterion; it is now used routinely in HEPP-ICE experiments.

I. INTRODUCTION

The ICE technique was first reported by Asay [4]. It yields accurate isentropic equation of state (EOS) data for various materials at Mbar-pressure in a planar geometry by magnetic loading. We have demonstrated the HEPP version of the ICE technique can also be used to obtain accurate (within 0.2% in pressure) isentropic EOS data at Mbar pressures in a planar geometry, and that the system is reliable, reproducible and predictable. With this system we may ultimately reach pressures of ~20 Mbar (2 TPa) with an advanced system [5].

For the precise control of pressure profiles in the HEPP-ICE experiment we needed closing switches that are capable: of withstanding ~150 kV without failure; of

closing to near zero voltage; of conducting currents of the order of 10 MA; and of closing with a timing precision of 25 to 50 ns. The original ICE circuit design used Procyon switches, which had been designed for another application. We incorporated four of these switches in parallel to optimize the current transfer. In practice we found switch timing jitter of the order of 600 ns, poor current transfer to our load and the voltage did not drop to zero across the switch when it closed. Thus we had two problems: timing; and closure impedance. We will describe the switch design; our analysis of the switch behavior; and a simple physical model that was shown to accurately describe the switch performance. Based on the model we have designed a new switch that has successfully met the requirements of the HEPP-ICE system.

II. SWITCH TIMING PRECISION

A. Procyon- switch design.

Two PBX-9407, 12.7-mm diameter x 12.7-mm long explosive pellets are detonated from the top in Figure 1a. The detonation wave travels downward and a shock wave is produced in the bottom of the aluminum metal cup which impacts a small ring air cavity. This develops a

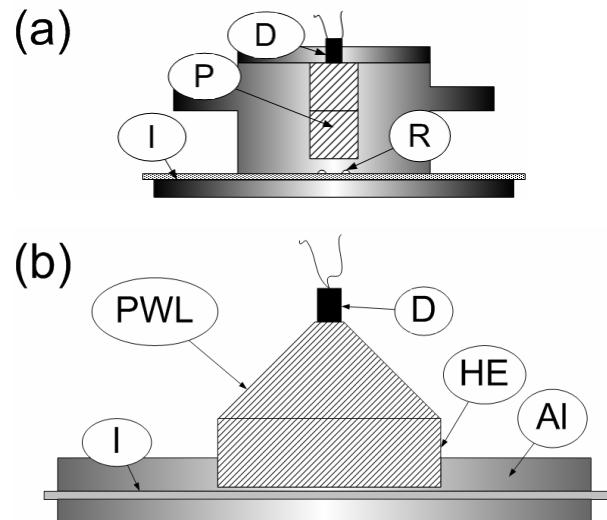


Figure 1. The two closing switch designs showing: the detonator D and the insulator I. a) Procyon switch: explosive pellets P; ring groove in the aluminum housing R. b) Polyimide switch: plane wave lens PWL; PBX-9501 disk HE; aluminum top and bottom electrodes Al.

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14. ABSTRACT Isentropic compression experiments (ICE) using a high explosive pulsed power (HEPP) system have been developed to obtain isentropic equation of state data for metals at megabar pressures [1][2]. The HEPP system comprises a magnetic flux compressor, an explosively-driven opening switch and a series of closing switches; fast rising current pulses are produced, with rise times of ~500 ns at current densities exceeding many MA/cm. These currents create continuous magnetic loading of the metals under study. The success of these experiments depends on the precise control of the current profile, and that in turn depends on the precise timing of the closing switches to within 50 ns at currents of the order 10 MA and voltages of ~150 kV. We first used Procyon closing switches [3] but found their timing to be unacceptably imprecise for ICE with a jitter of typically 600 ns. We suspected that the switch timing was sensitive to applied voltage; this was subsequently confirmed by experiment, as we will show. A simple shock model was developed to explain the voltage sensitivity of closure time, dt/dV, and from the model we designed a low jitter switch that uses the shock-induced electrical conduction of polyimide. The predicted dt/dV was exactly equal to the measured value, thus confirming the model. This new switch design proved successful and met the 50 ns criterion; it is now used routinely in HEPP-ICE experiments.				
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circular ring-shaped jet of aluminum, the slug, which is projected across an air gap into the 1.5-mm thick polyester insulation [6]. The circuit is closed when the slug has penetrated enough of the insulation for electrical conduction to occur, see section II.C.

It wasn't clear what was causing the poor timing but we suspected that the switch may be sensitive to voltage, i.e., the time to switch closure depended on the applied voltage. We therefore devised a series of tests where we applied a controlled voltage across a switch, via a charged transmission line, then fired the switch and measured the elapsed time from firing the detonator to when the current flow started.

B. Procyon-switch timing data

The results of the timing experiments with the Procyon switches are shown in Figure 2a, where the normalized time (measured – mean time) to switch closure is plotted against applied voltage. The switch closure times were clearly very sensitive to the applied voltage. The best (least squares) fit of the slope was $dt/dV = -3.4 \text{ ns/kV}$ with a standard error (SE) of the slope $\sigma_s = 0.68 \text{ ns/kV}$; the standard deviation (SD) of the data from the fit $\sigma_d = 107 \text{ ns}$. Clearly, such large uncertainties were unacceptable when 50 ns precision was sought. For example, the time to closure was increased by 480 ns as the voltage was reduced from 140 kV to zero. The consequences of these timing uncertainties for the ICE experiment are discussed in section III.

C. Explosive switch breakdown model

To understand the sensitivity to applied voltage we formulated a simple model of the switch. Consider the slug or conducting region penetrating the insulator at a velocity U , see Figure 3. As it does so the thickness of the insulation ahead of it is progressively reduced, and the electric field across it, $E_2(t)$, is progressively in-

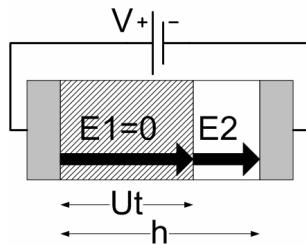


Figure 3. Simple switch model. A voltage V is applied across the electrodes. This establishes electric fields E_2 and E_1 ahead of the conducting region and behind it, where $E_1 = 0$. The conducting region grows with time from left to right at a velocity U .

creased as a function of time t . Given an initial insulation thickness h , we have $E_2(t) = V/(h - Ut)$. When $E_2(t) > E_{bk}$, the dielectric breakdown strength, the switch breaks down and currents flows in the switch. The breakdown voltage is

$$V_{bk}(t) = E_{bk}(h - Ut) \quad (1)$$

So the sensitivity of the timing to the applied voltage is

$$\frac{dt}{dV} = -\{UE_{bk}\}^{-1} \quad (2)$$

D. Procyon-switch model

For the Procyon switch the penetration velocity U has been calculated to be 1 km/s [7] and polyester has a breakdown strength of 180 MV/m. Hence we predict a voltage sensitivity $dt/dV = -5.56 \text{ ns/kV}$ compared to the -3.4 ns/kV we measured (this predicted line was arbitrarily drawn through the centroid of the data). The model

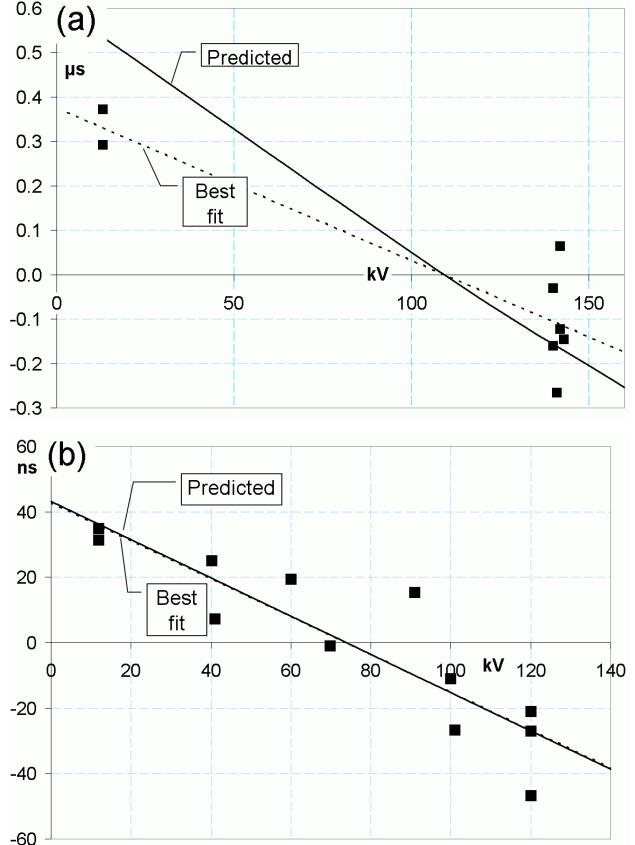


Figure 2. Normalized switch timing data vs. applied voltage in kV. a) Procyon switch, times in μs . b) Polyimide switch, times in ns. The black squares are the data; the dotted lines are the best fits; and the solid lines are the predictions.

predicts a larger but comparable sensitivity than we measured, but, even with the imprecision of the measured dt/dV (i.e., $\sigma_s = 0.68 \text{ ns/kV}$), the fit is beyond 3σ from the theory. As the slug penetration is subsonic (i.e., 1 km/s vs. 2.4 km/s for the ambient pressure sound speed in polyester) it projects a divergent precursor wave ahead of it which pre-compresses the polyester. We ignored this for the simple model, but it may induce conduction in the polyester [8], which would reduce dt/dV .

E. Polyimide-switch design

From Eq. (2) it is clear that in order to reduce dt/dV we must increase the product of E_{bk} , and U . From previous work we knew that electrical conduction can be induced

by pure shock in polyimide plastics [8][9][10]. Also, the shock velocity (U) is >6 km/s when shocked to pressures in excess of 20 GPa [11] and the dielectric strength is high, $E_{bk} = \sim 275$ MV/m [12]. Another design consideration was that we wanted to increase the conducting surface area of the switch to minimize the circuit impedance and improve its high current performance.

We therefore designed the polyimide closing switch shown in Figure 1b. It comprises a 100-mm diameter plane wave lens and PBX-9501 explosive disk inserted in a well of the top aluminum electrode; the bottom of the well is a 0.125-in (3.175 mm) thick aluminum disk. The top and bottom electrodes are insulated from each other by a 1-mm layer of polyimide insulation made from 2-mil and 3-mil (50- μm and 75- μm) thick sheets.

1) Polyimide-switch explosives manufacture

One minor drawback of the switch is that we must ensure that the explosive drive system (plane wave lens and explosive disk) is made to high precision from the same batches of explosives. Moreover, we must test every batch to ensure accurate timing. All this makes the polyimide switches more expensive to use than the Procyon switches.

F. Polyimide-switch timing data and model

The polyimide switch timing data are shown in Figure 2b. The best fit is $dt/dV = -0.58$ ns/kV, $\sigma_s = 0.1$ ns/kV, and the SD of the data from the line $\sigma_d = 13$ ns. Comparing these results with the Procyon switch ($dt/dV = -3.4$ ns/kV, $\sigma_s = 0.68$ ns/V, and $\sigma_d = 107$ ns) this new switch has significantly improved precision.

We calculated the shock velocity in the polyimide to be 6.2 km/s using shock-impedance mismatch calculations [13], the known JWL equation of state of the PBX-9501 explosive products [14], and the shock Hugoniots of 6061-T6 aluminum and polyimide [11]. Using Eq. (2), and given $E_{bk} = 275$ MV/m, the predicted $dt/dV = -0.59$ ns/kV; in fortuitously close agreement with the fit to the data (-0.58 ns/kV, $\sigma_s = 0.1$ ns/kV). It is important to note that, unlike the Procyon switch, the shock front traveling through the insulation in this switch is supersonic, so there is no acoustic precursor [15]. This probably accounts for the excellent agreement between the simple model predictions and the results.

III. PARALLEL SWITCH EFFECTS

The Procyon switch was not designed to take more than a few MA per switch, so we had to fire several of them in parallel to transfer the desired 5 to 7 MA to the ICE load in ~500 ns. To do this we had to balance the currents between the switches, which meant that all the switches must close simultaneously; yet the chances of simultaneity were small because the SD of Procyon switch closures was ~100 ns (independent of voltage sensitivity), see II.F. We needed to estimate the effects on non-simultaneity of current balance between switches.

In other work we had developed an accurate dynamic simulation of the ICE circuit [16]. Based on our switch model (II.D) we incorporated three parallel circuits representing the closing switches into our ICE simulation. The switch simulation was based on the simple model (II.C) where the breakdown voltage varied according to Eq. (1).

A. Effects of dt/dV on switch closure

1) Procyon

From experimental results we estimated the inductance and resistance of each Procyon switch on closure was 8 nH and 3 mohm at the pertinent current levels, and we set the jitter between the three parallel switches to 100 ns (the experimental value) to show the effects of dt/dV . The value of dt/dV we used was -5.56 ns/kV from II.D.

The calculations showed that as soon as the first switch (X1) closed the voltage across all three switches fell by -50 kV in 10 ns (we needed it to fall by -100 kV for good current transfer). Consequently the other two switches (X2 and X3) were delayed by -50 kV \times -5.56 ns/kV = 278 ns in addition to the jitter (100 ns). The results of the simulation are seen in Figure 4a. X1 was the only switch to conduct for the first 357 ns, and this resulted in poor

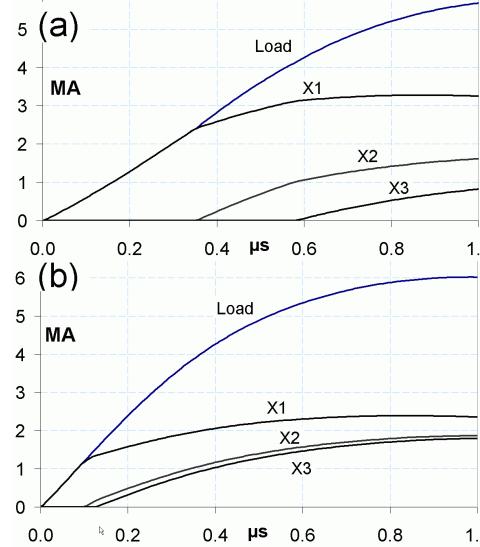


Figure 4. Simulation of the total ICE load current (Load) with currents in the three parallel switches (X1 to X3): a) Procyon; b) Polyimide. Currents in MA; times in μs ; the plot scales are the same.

current transfer to the load. (The results of our simulations with 10-ns delays were similar.) The initial rate of rise of the current, dI/dt , to the load was 6 TA/s and the current reached only 3.5 MA in 500 ns.

This clearly demonstrates that the effects of the large dt/dV are sufficient to allow only one switch to effectively conduct. Moreover, the effect of dt/dV is much more significant than the jitter between switches (at the same voltage), i.e., a 10 ns jitter still led to a 300 ns delay.

2) Polyimide

We performed the same circuit simulation on three parallel polyimide switches [17]. Here we used the polyim-

ide switch model and, from experimental data, 0.5 nH and 100 μ ohm for the switch impedance and 25 ns for the jitter. All other circuit parameters were the same as for the Procyon simulation. The results in Figure 4b show a significant improvement over the Procyon switch. With polyimide the switch currents are more closely matched to each other, and the initial dI/dt in the load is doubled to 12 TA/s. The load current reached 5 MA in 500 ns as required. (As the magnetic pressure varies as the current squared the pressure doubled from the Procyon to polyimide simulations.) The voltage across the first switch fell by -120 kV in 5 ns to near zero, so the calculated effect of dt/dV is $-120 \text{ kV} \times -0.59 \text{ ns/kV} = 71 \text{ ns}$. The combined effect of this delay and the jitter was 99 ns and 125 ns in the simulation.

When performing the actual ICE experiments we found that the polyimide switch worked better than predicted. We measured currents in each switch and found that they were balanced to within 5% of each other. This appears to be due to high frequency ringing at the time of switch closure, which reduces the effect of dt/dV .

IV. SUMMARY AND CONCLUSIONS

For isentropic compression experiments (ICE) using a high explosive pulsed power (HEPP) system we needed to transfer currents of 5 to 7 MA or more with risetimes of \sim 500 ns. To do this we had first tried using Procyon closing switches, which operate by projecting a jet of aluminum through a polyester insulator, but we found their timing to be unacceptably imprecise for ICE with a jitter of typically 600 ns. We suspected that the switch timing was sensitive to applied voltage and this was subsequently confirmed by experiment. We developed a simple shock model to explain the voltage sensitivity, dt/dV , and the predicted sensitivity was found to be similar but larger than the measured values. The difference is thought to be due to a shock precursor in the insulation.

We incorporated the model into simulations of the ICE circuit. The results matched those of the experiment closely, and confirmed that the poor current transfer was most likely due to the dt/dV timing sensitivity.

Based on the model we designed a faster switch based on the shock induced conduction of polyimide [15]. Within the precision of the data the predicted dt/dV was equal to the measured value, thus confirming the model.

One minor drawback of the polyimide switch is that, for predictable and accurate timing, we must ensure that the explosive drive system is made to high precision from the same batches of explosives. Moreover, we must test every batch to ensure accurate timing. All this makes these switches expensive.

We have successfully used the polyimide switch in many HEPP-ICE experiments and obtained the desired current profiles and isentropic equation of state data. It is now used routinely in HEPP-ICE experiments.

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- [15] We inserted a 10- μ m thick aluminum foil as a shock arrival detector between the bottom of the top electrode and the top of the polyimide (not possible with the Procyon switch). This verified that conduction started within 160 ns, i.e., during the first wave transit through the insulation, and was shock induced.
- [16] Using a generic SPICE circuit code by Top-SPICE/Win32 v7.0 circuit code, Penzar Development, P.O. Box 10358, Canoga Park, CA 91309, U.S.A. The details of our model are omitted for lack of space.
- [17] We may not need more than one polyimide switch in the ICE experiment, but dare not risk a shot failure by using just one.